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Statistical analysis of construction tolerances in asphalt pavements

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Statistical analysis of construction tolerances in asphalt pavements

by

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ABSTRACT

Iowa Department of Transportation (DOT) manages construction quality in asphalt pavements through a combination of Specifications (SPEC), Instructional Memoranda (I.M.) and field control. Upon approval of Job Mix Formula (JMF) submitted by the contractor, it becomes the target during the field production. During production, samples are taken from the production mix, and the measurements made on samples are recorded on Daily Plant Report (DPR). Through continuous monitoring and testing, the field products are controlled to consistently conform to the JMF, and are considered satisfactory when their deviation from JMF is within the tolerances specified in SPEC and I.M.. Thus, proper evaluation of construction quality is possible under the condition that the specified tolerances are rational and achievable.

This study was undertaken to re-evaluate currently specified tolerances established mainly pre-1995, using field data obtained from recent historical projects. To achieve this goal, a database was set up with 56 projects constructed across Iowa during the last 3 years, and statistical analysis of the data was performed on volumetric and compaction factors of hot mix asphalt (HMA) such as, percent lab-voids (Pa), percent field-voids (%Voids), percent field compacted density (%Density), asphalt content (%AC), film thickness (FT), fines to bitumen ratio (F/B), voids in mineral aggregate (VMA), voids filled with asphalt (VFA), theoretical maximum specific gravity (Gmm & %Gmm), and aggregate gradations. The mean and standard deviation of each factor was calculated, and its difference from the target as well. The statistical analysis also involved validating currently specified tolerances, identifying the distributional characteristics of the data and examining the existence of the regional difference of

those factors.

The results of this study showed that the volumetric and other properties of HMA mix produced in the field were within the specified tolerances and the production was reasonably consistent. Also the construction tolerances currently specified in SPEC & I.M. could be considered, generally, reasonable and achievable.

Adjusted statewide standard deviations are proposed, which if used to set tolerances, would allow each district to meet the 5% rejection criterion.

CHAPTER 1. INTRODUCTION

There have been many efforts to improve the design procedure for hot mix asphalt (HMA) mixtures and pavement structures, which are anticipated to enhance the quality of HMA pavements, and extend their service life. One example of the innovative development in mix design would be the advent of SUPERPAVE (Superior Performing Asphalt Pavement).

Even though design methods are continuously studied and improved, there is still a fact that should be realized; there is always some discrepancy or variation between the laboratory-prepared specimen and the final field products. Therefore, reducing this gap provides another way to contribute to ensuring the high quality/performance of HMA pavements. The quality-related terms such as, Quality Control (QC), Quality Assurance (QA), and Total Quality Management (TQM), have been issued for this reason.

Construction quality is examined to determine how closely and consistently the products conform to the design target, once the target is identified. In asphalt pavement construction, the target is the Job Mix Formula (JMF), and the field product, which is the mixed, placed, and compacted HMA mixture is tested and monitored to compare with the properties defined in JMF. If the products meet the criteria specified, or the deviations from the targets are within tolerance, they are considered satisfactory. Thus, the first concern to be addressed is whether the standards (tolerances) on which the quality-evaluation depend are appropriate, to ensure the quality of HMA pavements.

In Iowa, Specifications (SPEC) and Instructional Memoranda (I.M.) prepared by the Department of Transportation (DOT) are used to specify the construction tolerances. This study was undertaken to re-evaluate the current construction tolerances in asphalt pavement for reasonableness and to make recommendations to correct any deficiencies found, and to suggest alternate QC/QA procedures.

CHAPTER 2. OBJECTIVES

Iowa Department of Transportation (DOT) manages construction quality in hot mix asphalt (HMA) pavements through a combination of specifications (SPEC), instructional memoranda (I.M.), and field control. The SPEC and I.M. set standards required to be satisfied by the products in HMA pavement construction. The contractor submits material samples and a proposed job mix formula (JMF). This is a mix design of HMA mixture developed in the laboratory using the job site-available aggregates and asphalt, satisfying the requirements of the SPEC and I.M.. Upon approval of the JMF, it becomes the target for field production. The DOT monitors the production to maintain quality within SPEC tolerances with respect to the JMF and SPEC.

Since it is believed that the quality of HMA pavements depends primarily on the volumetric and other properties of the compacted mixture, the SPEC and I.M. prescribe the tolerances, the acceptable degree of variations, of those factors; such as gradations of aggregates, air voids, density, asphalt content, film thickness, fines to bitumen ratio, voids in mineral aggregates, and voids filled with asphalt. During production, the contractor submits a Daily Plant Report (DPR) to record measurements made on samples taken from the production mix, both loose and compacted.

Comparing volumetric and other factors in DPR with the tolerances provided in SPEC and I.M. makes it possible to evaluate the quality, or consistency, of HMA production conducted by the contractor: how closely and consistently the field products are produced to JMF. Therefore, to properly determine the quality of the project, the tolerances not only should be rational but also should be achievable by the contractors.

The purpose of this study is to re-evaluate currently specified tolerances established mainly pre-1995, using field data obtained from recent historical projects. To achieve this goal, the following primary tasks have been undertaken:

Task 1. Data collection

Task 2. Statistical analysis of data

Task 3. Re-evaluation of currently specified construction tolerances

To accomplish Task 1, data were gathered from 56 projects constructed across Iowa during last 3 years and a database was set up to contain all information on projects including their JMF and DPR.

In Task 2, volumetric and other factors in DPR were analyzed statistically, and the mean, standard deviation and the difference from target value (SPEC, I.M., JMF) of each factor were calculated to revalidate the tolerances. One specific sub-objective in Task 2 was to determine whether or not regional differences exist in volumetric and other factors. Since aggregates (which constituting over 80% of the total volume of a mixture) may have slightly different properties depending on the local geology and production equipment, regional differences are a distinct possibility. Another sub-task of Task 2 was to identify the characteristics of the distributions of the data, using various statistical methods.

In summary, this project seeks to re-evaluate construction variability by examining production records, and to recommend reasonable tolerances for the acceptance of HMA production.

CHAPTER 3. DATA DESCRIPTION

This chapter defines the information provided on the Job Mix Formula (JMF) and Daily Plant Report (DPR) forms. Relevant terms and formulas are explained.

3.1 Job Mix Formula

HMA mix design consists of three major steps: (1) aggregate selection, (2) asphalt binder selection, and (3) design asphalt content (AC) determination. Initial JMF is established through these steps in the laboratory, while satisfying all relevant criteria in each step. After approval by the DOT, HMA pavement project is launched with the JMF as a target and, if necessary, the JMF may be adjusted with the field data. Iowa DOT I.M. 511 B (1997) describes the JMF as 'a single percentage of aggregate passing each required sieve size and a single percentage of each material, including the asphalt content, to be used in the mixture'.

The projects used in this study utilized two mix design methods. One is the Marshall method developed by Bruce Marshall and enhanced later by the Corps of Engineers. The other is SUPERPAVE (Superior Performing Asphalt Pavement) mix design, which resulted from the SHRP (Strategic Highway Research Program) study. Figure 1 is a typical example of the JMF of Marshall method and Figure 2 is that of SUPERPAVE. Although these two JMFs are prepared through quite different procedures in accordance with the mix design method, this form (officially named 'Form 956') consists of five common major parts. The first part describes general information about the project. The second and third parts define the aggregates sources and their blended gradation including the tolerances of each sieve size as specified in Standard SPEC 2303.02.

IOWA DEPARTMENT OF TRANSPORTATION
OFFICE OF MATERIALS
ASPHALT CONCRETE MIX DESIGN
LAB LOCATION AMES

MATERIAL: TYPE A — LAB NO.: ABD8-6007
INTENDED USE: SURFACE — CONTRACT NUMBER:
SIZE: 3/4 in. SPEC. NO.: GS95002M — DATE REPORTED: 05-19-1998
COUNTY: JOHNSON — PROJECT: STPN-1-6(22)--2J-52
CONTRACTOR: L.L. PELLING — ADT: 4150
PROJ. LOCATION: HWY.1. SOUTH MT VERNON

AG. SOURCES: SAND-S&G MATERIALS SO. STEVENS PIT @ 25%
MAN SAND-TA-T4 RPC; CONKLIN BEDS 3-10 @ 21%
3/8" TYPE A-RPC; KLEIN- BEDS 3-10 @ 28%
3/4" TYPE A-RPC; KLEIN- BEDA 3-10 @ 11%
SLAG-HECKETT, STERLING, IL. @ 15%

JOB MIX FORMULA-COMBINED GRADATION

	1-1/2	1	3/4	1/2	3/8	#4	#8	#16	#30	#50	#100	#200
	100	100	100	93	83	60	44	31	20	8.3	3.7	3.2
TOLERANCE			98/100	7	7	7	5		4			2

ASPHALT SOURCE AND GRADE: PG58-28 KOCH @ LINWOOD

% ASPHALT IN MIX	4.25	5.49	5.60	6.25
NUMBER OF MARSHALL BLOWS	50	50	50	50
MARSHALL STABILITY LBS.	7540	7181	7148	7606
FLOW - 0.01 IN.	7	8	8	10
MARSHALL SP GR-LAB DENS.	2.391	2.431	2.435	2.455
BULK SP GR COMBINED AGGR	2.716	2.716	2.716	2.716
SP. GR. ASPHALT @ 77 F	1.027	1.027	1.027	1.027
CALC. MAX. SP. GR.	2.584	2.533	2.528	2.499
CALCULATED % VOIDS	7.47	4.00	3.68	1.76
MAX. SP. GR. - RICE	2.584	2.533	2.528	2.499
% VOIDS - RICE	7.47	4.00	3.68	1.76
% WATER ABSORPTION AGGR	0.70	0.70	0.70	0.70
% VOIDS IN MINERAL AGGR	15.71	15.40	15.37	15.26
% V.M.A. FILLED WITH AC	52.45	74.06	76.06	88.46
FILM THICKNESS-MICRONS	8.59	11.68	11.96	13.70
FILLER/BITUMEN RATIO	0.75	0.58	0.57	0.51
EFFECTIVE SP GR - AGGR	2.770	2.767	2.768	2.763
CALC. % AC ABSORPTION	0.74	0.70	0.71	0.64
CALC. BULK SP. GR.-AGGR.	2.745	2.741	2.742	2.737

MINIMUM %AC FOR THIS AGGREGATE COMBINATION IS 5.07%

DISPOSITION: AN ASPHALT CONTENT OF 5.5% IS RECOMMENDED TO START THE JOB

COMMENTS: CONTRACTOR QMA MIX DESIGN VERIFIED BY ECITC LABORATORY
GRADATION ALSO CONTROLLED BY FILLER/BITUMEN RATIO. 3.0% MINIMUM PASSING THE #200 SIEVE.
RESULTS SHOWN IN 5.49 COLUMN ARE INTERPOLATED FROM TEST DATA.

COPIES TO: CENTRAL LAB L.L. PELLING BIT. ENGINEER
BOULET LOHRER YANNA LABORATORY

SIGNED: R. H. BOULET P.E.
ENGINEER

Figure 1. An example of Job Mix Formula based on Marshall method

Form 956

Iowa Department of Transportation
Project Development Division - Office of Materials
ACC Superpave Mix Design

County :	Audubon	Project :	NHS-71-4(26)–19-05	Lab No. :	SWI9-34
Size :	19 mm	Contracter :	Mannatts Inc	Contract No. :	
Mix Type:	B	Design Life ESAL's	333,333	Date Reported :	07/15/99
Intended Use :	Base	Proj. Location :	North Of Audubon		

Agg. Sources : 3/4 CL	A01004	Schildberg Jefferson	@	20.0%
1/2 Stone	A01004	Schildberg Jefferson	@	34.0%
1/2 ST Washed	A01002	Schildberg Menlo	@	15.0%
Sand	A05506	Hallett Exira	@	16.0%
RAP		Project 5.66% AC GSB=2.599 Abs=1.26	@	15.0%

Job Mix Formula - Combined Gradation (Sieve Size mm)

	25	19	12.5	9.5	4.75	2.36	1.18	600μ	300μ	150μ	75μ
* Upper Tolerance	100	100	90	82	54	35	22	17	14		7.4
	100	99.9	88	75	47	29	22	16	8.8	5.7	4.4
* Lower Tolerance	100	93	81	68	40	23		11			2.0

Asphalt Source and Grade: Koch Omaha PG 58-28

	Gyratory Data				Interpolated
% Asphalt	4.00	4.50	5.00	5.50	4.68
Corrected Density @ N-Design	2.336	2.343	2.350	2.363	2.346
Max. Sp.Gr. (Gmm)	2.481	2.452	2.428	2.413	2.443
% Gmm @ N- Initial	85.32	86.14	86.98	87.45	86.45
% Gmm @ N-Max	95.38	96.84	98.19	99.34	97.33
% Air Voids	5.84	4.45	3.21	2.07	4.00
% VMA	13.11	13.31	13.50	13.48	13.38
% VFA	55.45	66.57	76.22	84.64	70.05
Film Thickness	7.37	8.96	10.38	11.44	9.47
Filler Bit. Ratio	1.38	1.13	0.98	0.89	1.08
Gsb	2.581	2.581	2.581	2.581	2.581
Gse	2.637	2.624	2.616	2.619	2.624
Pbe	3.19	3.88	4.49	4.95	4.10
Pba	0.84	0.65	0.53	0.58	0.65
% New AC	79.45	81.83	83.73	85.29	82.56
AC Sp.Gr. @ 25c	1.026	1.026	1.026	1.026	1.026
% Water Abs	1.66	1.66	1.66	1.66	1.66
S.A. m^2 / Kg.	4.33	4.33	4.33	4.33	4.33
% +4.75mm Friction Agg.	0.0	0.0	0.0	0.0	0.0
Angularity-method A	41	41	41	41	41
% Flat & Elongated	0.0	0.0	0.0	0.0	0.0
Coarse Agg. Angularity	*97/97	*97/97	*97/97	*97/97	*97/97
Sand Equivalent	95	95	95	95	95

Avg. Design High Air Temp. C
<39

mm from Surface
100

Number of Gyrations
N-Initial
7
N-Design
76
N-Max
117

Gsb for Angularity
Method A
2.619

Slope of Compaction
Curve
11.25

Disposition : An asphalt content of 4.68% is recommended to start this project.
Data shown in 4.68% column is interpolated from test data.
* Gradation tolerances shown have been adjusted to stay within the control points.

Comments : SWI9-34 For Mix Design #4BD9-27
Start at 4.50% AC

Copies to : Mannatts Inc SWI Dist Lab

Signed

Figure 2. An example of Job Mix Formula based on SUPERPAVE method

In the middle of this form as the fourth part, asphalt grade and the properties of a number of trial mixtures are shown in detail. The last part of JMF includes a material engineer's comments and recommendations, and some other miscellaneous information. The data used in this study are taken from part 3 and 4, JMF, shown in the midst of JMF form.

3.1.1 Combined gradation

The combined gradation of aggregates illustrated in part 3 of JMF form shows a single percentage by weight of aggregates passing each sieve size and their tolerances. Individual aggregates may come from several sources, and will have met chemical and other physical requirements (Standard SPEC 4126 & 4127). These are blended to satisfy the gradation criteria specified in Supplemental SPEC 97055 and I.M. 510 (Table 1), using one of the aggregate blending methods, such as trial-and-error method, graphical methods and computer software (e.g. SHADES).

The distribution of the combined aggregates (blend) determined through these procedure becomes the target distribution of the field products and, for quality control purposes, the contractor must maintain gradations of field products within the production tolerances specified in Standard SPEC 2303.

3.1.2 Asphalt grade

In Iowa, the SUPERPAVE Performance Grading (PG) system has been implemented since 1994, and AC viscosity-graded asphalt may approximately correspond to PG grades as follows: AC-5 &10 to PG 58-28, and AC-20 to PG 64-22 (Standard SEPC 2303.02) [1].

Table 1. Aggregate Gradation Table cited from IDOT Standard SPEC 4109.01

	Percentage of aggregates passing each sieve size			
	Maximum size			
	25.0 mm	19.0 mm	12.5 mm	9.5 mm
37.5 mm	100			
25.0 mm	92 – 100	100		
19.0 mm	77 – 92	98 – 100	100	
12.5 mm	60 – 80	76 – 92	92 – 100	100
9.5 mm		60 – 85	70 – 91	98 – 100
4.75 mm	34 – 55	42 – 67	50 – 72	63 – 89
2.36 mm	20 – 39	30 – 53	36 – 57	44 – 68
600 μm	7 – 20	14 – 32	16 – 34	20 – 37
75 μm	2 – 7	3 – 7	3 – 7	3 – 7

The PG grading system is primarily based on environmental conditions appropriate to the project location. The climatic information is available from a weather database (LTPPbind) managed with 6,500 reporting stations in U.S. and Canada. The database provides the seven-day average high pavement temperature, the lowest pavement temperature, their means and standard deviations based on over 20 year records [2]. The most common grade in Iowa, PG 58-28 means that binder satisfies its physical property requirements over the range: 58°C to –28°C.

3.1.3 Properties of mixture

Although the procedure to determine the optimum asphalt content is slightly different between the mix design methods (Marshall & SUPERPAVE), generally a series of trial specimens are prepared using different amount of asphalt with 0.5%

increments. After performing required mix design tests to measure HMA properties listed in Figure 1 and 2, the asphalt content corresponding to 4% (typically) air voids is considered the optimum [3], if all other parameters are met. If the properties of that sample calculated and measured or interpolated on the basis of 4% air voids, meet all criteria in SPEC, that then becomes the design asphalt content and the values in the column under the optimum AC are regarded as target properties that field produced mixtures should achieve during construction and/or within a few service years. The initial JMF is completed after consultation with and approval of the DOT. However, there are allowances to permit adjustment during early production.

3.2 Daily Plant Report

During HMA pavement construction, the contractor produces and places HMA as close to the JMF as possible, and the day's products (both loose mix and compacted mixture) are sampled and tested in the contractor's quality control field laboratory to ensure that their quality is satisfactory. The test data, thus obtained are documented in the DPR as shown in Figure 3 and submitted to DOT. The left half of the DPR provides the volumetric properties and aggregate gradations of the loose mix sample, and the right hand side contains those of the compacted pavement sample and other calculated factors using the values from both loose and compacted sample.

3.2.1 The loose mix

Testing on the loose mix is performed to check that the produced mix is effectively the same as that approved by the JMF.

800241M - 01/99

DAILY ACC PLANT REPORT

Project No.: IM-80-2(161)173--13-01 Contractor: Manatts Class: Superpave Report No.: 11

Contract ID: 91741 County: Adair Size: 19mm Design Blows:

Mix Design No.: 4BD9-3 Recycle Source: Mix Type: A Design Gyrations: 109

Hot Box I.D. No.:		0817-A	0817-B	0817-C	0817-D	
Date Sampled:		08/17/99	08/17/99	08/17/99	08/17/99	
Gradation ID:	Specs	08/17/99-A	0817-B		Avg.	
25mm Sieve	100	100	100	100	100	
19mm Sieve	93-100	100	100	100	100	
12.5mm Sieve	83-90	92	87	89	89	
9.5mm Sieve	72-86	83	80	82	82	
* 4.75mm Sieve	48-62	57	55	56	56	
* Moving Average		56	56	56		
* 2.36mm Sieve	28-35	33	34	33	33	
* Moving Average		34	34	34		
1.18mm Sieve		20	22	21	21	
* 600um Sieve	8.6-17	13	14	13	13.3	
* Moving Average		15	14	14		
300um Sieve		6.6	6.8	6.4	6.6	
150um Sieve		4.2	4.3	3.8	4.1	
* 75um Sieve	2.0-5.4	3.5	3.6	3.0	3.4	
* Moving Average		3.8	3.8	3.6		
Compliance (Y/N)		N	Y	Y	[redacted]	
Intended Added, % AC	5.40					
Actual Added, % AC		5.38			5.38	
Intended Total, % AC	5.40					
Actual Total, % AC		5.38			5.38	
Gmb:		2.370	2.389	2.383	2.381	
Gmm:		2.494	2.492	2.486	2.490	
Pa:		5.0	4.1	4.1	4.4	
Moving Average	3.5-5.0	4.7	4.7	4.6	4.4	
Time		8:45	12:20	2:05	5:35	
Station		126+49	105+15	93+57	74+22	
Side		WBDL	WBDL	WBDL	WBDL	
Sample Mg's		200.00	1,233.00	1,699.00	2,588.00	
Sublot Mg's		500.00			2,419.86	
Mg's to Date					16,930.56	
Fines / Bitumen Ratio	.60-1.40	0.82			0.79	

Gsb: 2.628 Gb: 1.0330 Effective % AC: 4.28

Time	7:00	9:00	11:00	1:00	3:00	5:00	7:00
Air Temp. (°C)		21.5	26.6	30	30.6	30.6	
A.C. Temp. (°C)		146.5	148.9	148.9	146.5	143.3	
Mix Temp. (°C)		161.6	161.6	156.2	157	157	

Date Placed: 08/17/99 Date Tested: 08/18/99

Course Placed: Surface Tested By: Larry

Density Record

Core No.:	1	2	3	4	5	6	7
Station	126.74	119.94	109.59	102.51	91.87	83.19	74.30
CL Reference	2.35 RT	3.19 RT	.65 RT	1.25 RT	.80 RT	2.89 RT	1.78 RT
W 1 Dry	2,064.5	2,047.6	2,037.4	2,031.1	2,129.7	2,308.4	1,970.4
W 2 in H20	1,173.8	1,162.0	1,151.8	1,150.6	1,213.1	1,311.1	1,108.3
W 3 Wet	2,067.1	2,050.8	2,039.0	2,031.9	2,131.2	2,309.5	1,972.9
Difference	893.3	888.8	887.2	881.3	918.1	998.4	864.6
Field Density	2.311	2.304	2.296	2.305	2.320	2.312	2.279
% Density	97.080	96.766	96.430	96.808	97.438	97.102	95.716
% Voids	7.2	7.5	7.8	7.5	6.9	7.2	8.5
Thickness (mm)	56	56	56	56	56	61	53

Gmb (Lot Avg.): 2.381 Avg. Field Density: 2.304

Gmm (Lot Avg.): 2.491 Avg. % Density: 96.760

TC Labs Pa: Avg. % Field Voids: 7.5

Target % RAP: 8.0 Specified % Density: 96

$$Q.I. = \frac{96.760 - 96.000}{0.558} = 1.36$$

Low Outlier: High Outlier: New Q.I. =

Film Thickness (FT): 11.7 VMA: 14.3

Remarks: Sta; 131+36 thru 66+78

Mix Change Information:

C.P.I.: Jeff Jenkins NWO86 Cert. No.

QMA Tech: Larry Clarke CI407 Cert. No.

Distribution: ___ Central Materials ___ TC Materials ___ Proj. Engineer ___ Contractor ___ Plant

Figure 3. An example of Daily Plant Report

The first factor in DPR is aggregate gradations based on cold feed gradation. The single percentage passing each sieve size should be regulated within production tolerances and consistently conform to the JMF as a target value. In Iowa, four sieve sizes are reviewed to control the production quality of the combined aggregates as shown in Table 2, with their associated tolerances.

However, a precaution needs to be taken for using this table. Since gradation values also should meet the Aggregate Gradation Table shown in Table 1, the acceptable range of each sieve size is not always a percentage in JMF plus and minus its tolerance. For example, if the percentage passing 75μm in JMF of type B mix with 19mm maximum size is 3.9, the acceptable range for 75μm sieve is 3 to 6.9, not 0.9 to 6.9.

The other factors are Asphalt Content (AC), Bulk Specific Gravity of Mixture (Gmb), Maximum Theoretical Specific Gravity of Mixture (Gmm), Percent Air Voids (Pa), and Fines to Bitumen ratio (Dust Proportion, F/B).

To determine these volumetric factors, the loose HMA mix is taken, at random, behind the paver, prior to compaction, and tested. Table 3 shows their tolerances specified in the SPEC.

Table 2. Aggregate gradation tolerances provided in Standard SPEC 2303.02

Sieve Size	Target Values	Specification Tolerances	
		Type A Mix	Type B Mix
4.75 mm	by JMF	± 7	± 7
2.36 mm	by JMF	± 5	± 6
600 μm	by JMF	± 4	± 5
75 μm	by JMF	± 2	± 3

Table 3. Production tolerances of the loose mix

Volumetric Factors	Target Values	Specification Tolerances
Asphalt Content (AC)	by JMF	–0.3 / +0.3
	3.0	–0.5 / +1.0
Percent Air Voids (Pa)	3.5	–0.5 / +1.0
	4.0	–0.5 / +1.0
Fines to Bitumen Ratio (F/B)	—	+0.6 / +1.4

For the sampling purpose, the day's production is regarded as a LOT and the first 500 tons of each day is a SUBLOT. The rest of the production quantity is divided into three equal SUBLOTs or each 750 tons after the first 500tons is SUBLOT depending on the total quantity of production in that day. A sample is taken from each SUBLOT and the number of samples each day is at least one but no more than four (I.M. 511 QMA).

The samples transported to the field laboratory are compacted and/or tested in accordance with specified I.M.s to determine Gmb, Gmm, Pa, and F/B. Asphalt content is currently determined by the tank-stick measurement averaged by the total quantity of production.

3.2.2 The compacted mixture

Since the characteristics of materials and mixture placed change with time, continuous monitoring and evaluation of the final products should be performed. The right hand side of DPR records the volumetric properties of the compacted mixture, and seven pavement core samples (density samples) are taken in each day for this purpose. Again, these properties should be regulated within their tolerances as shown in Table 4.

Table 4. Production tolerances of the compacted mixture

Volumetric Factors	Target Values	Specification Tolerances
% Voids	—	Type A mix → 4.0 / 8.0 Type B mix → 3.0 / 8.0
% Density	94 % 95 % 96 %	Minimum Minimum Minimum
Film Thickness (FT, microns)	—	Wearing courses → 8.0 / 13.0 Non-wearing courses → 7.5 / 13.0

Factors described in the Density Record of DPR are determined by the following equations:

- Field Density $= \dfrac{W_{Dry}}{W_{SSD} - W_{Sub}} = \dfrac{W1}{W2 - W3} = G_{mb,FIELD}$

  where, W_{Dry} = the weight of mixture in dry condition

  W_{SSD} = the weight of mixture in saturated surface dry condition

  W_{Sub} = the weight of mixture submerged in water

- %Density $= \dfrac{Field\ \ Density}{G_{mb}\ (Lot\ Avg.)} \times 100 = \dfrac{G_{mb,FIELD}}{G_{mb,LAB}} \times 100$

  where, $G_{mb,FIELD}$ = bulk specific gravity of the field compacted mixture

  $G_{mb,LAB}$ = bulk specific gravity of the lab compacted loose mix

- %Voids $= \left(1 - \dfrac{G_{mb,FIELD}}{G_{mm}\ (Lot\ Avg.)}\right) \times 100 = \left(1 - \dfrac{G_{mb,FIELD}}{G_{mm,LAB}}\right) \times 100 = VTM_{FIELD}$

  where, $G_{mm,LAB}$ = theoretical maximum specific gravity of the loose mix

  VTM_{FIELD} = voids in total mix of the compacted mixture

Q.I. below the Density Record table indicates the Quality Index for density determined by

- $\text{Q.I. (Density)} = \dfrac{\textit{Average \%Density} - \textit{Specified \%Density}}{\textit{Std. Deviation of \%Density Measurements}}$

Only one outlier out of seven samples is allowed to be excluded from the Q.I. calculation, if properly identified with specified procedure (I.M. 508). Q.I. is somewhat important to both the contractor and the DOT since it is an obvious tool for the contractor to decide whether adjustments to control the quality of the field products are necessary or not, and this is used currently as the basis of payment.

Other volumetric factors in DPR are calculated as follows:

- $\text{Film Thickness (FT)} = \dfrac{P_{be}}{SA} \times 10$

  where, P_{be} = effective asphalt content (%)
  SA = surface area of the combined aggregate (m^2 / kg)

- $\text{Voids in Mineral Aggregate (VMA)} = \left\{1 - \dfrac{G_{mb,LAB}(100 - P_b)}{G_{sb}}\right\} \times 100$

  where, P_b = asphalt content (%), AC
  G_{sb} = bulk specific gravity of the combined aggregate

3.3 Data Collection

To construct the database for this study, recent historical project records were obtained from Iowa DOT. Table 5 shows the data sizes used in this study.

The database contains 1,552 DPRs under 231 JMFs of recent historical projects conducted in 39 counties of Iowa, and as illustrated in Figure 4, the database was built to include nearly all information about the projects, especially volumetric properties of

HMA mix in JMF, and those of the loose and compacted mix in DPR, in order to perform statistical analysis about those factors.

Table 5. Data sizes used in this study

Proposals (by letting year)	1996	1997	1998	1999
	1	11	20	15
Total		47		
Projects (by letting year)	1996	1997	1998	1999
	1	11	25	19
Total		56		
Job mix formula		231		
Daily plant report		1552		
County		39		
Construction Length		903 km		

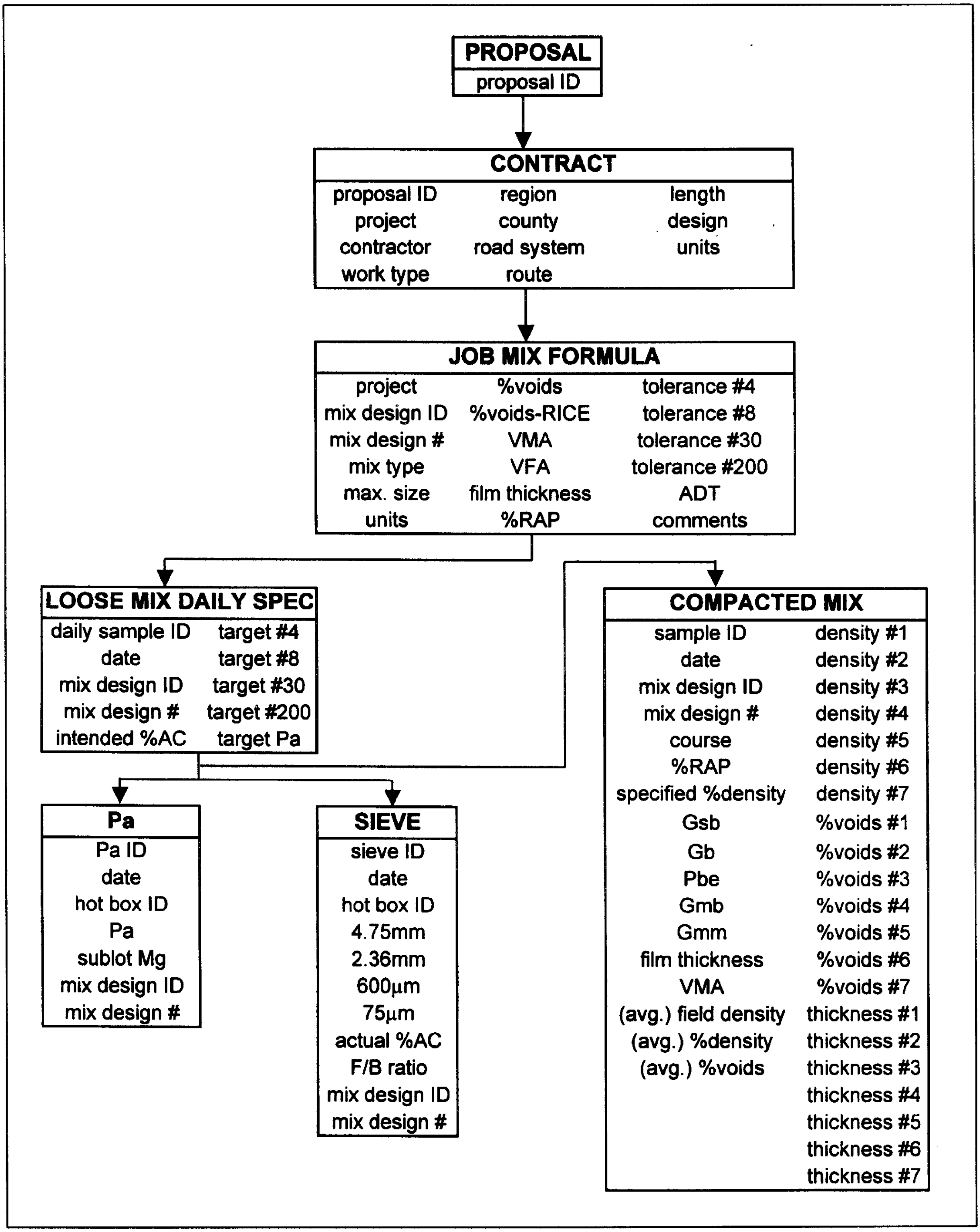

Figure 4. Structural description of database

CHAPTER 4. DATA AND SUMMARY

In this chapter, terms are defined and current requirements or limits discussed. A summary of data statistics is provided for each factor presented.

During the period of this study, there were several meetings with material engineers at the Iowa DOT to discuss which volumetric and other properties of HMA pavement should be examined; which ones are more critical, and how the contractors control the quality of their products in the field. For the objectives of this study and for further study, as many volumetric factors as possible described in JMF and DPR were analyzed statistically, even though some of them are not specified in SPEC or I.M..

Once each factor was evaluated with its specified tolerance on a statewide basis, the data were grouped by regions (Figure 5) and re-analyzed to determine whether significant regional differences exist. In general, the aggregates used in HMA are provided from local sources and thus, the properties of the aggregates may strongly reflect local geology. Different characteristics of HMA mix by regions, related to aggregates are distinctly possible in its performance as well as volumetric properties during production.

A total of 11 factors were selected as below. Each factor was sub-divided by its target value or mix type, and the mean and standard deviation of each was calculated from project records. To examine production-consistency and conformity to target, the deviations from target values were reviewed wherever possible, and when the target is JMF, the number of samples are less than those of DPR, due to limited number of JMF provided.

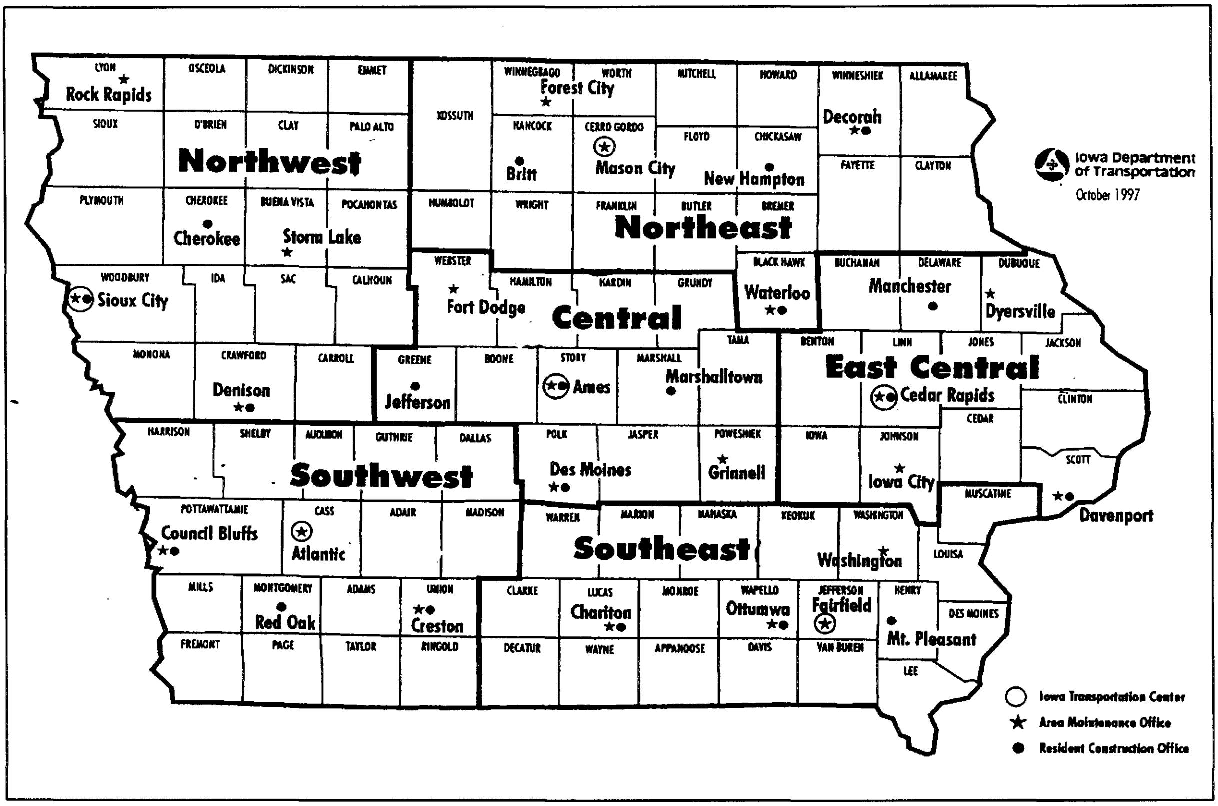

Figure 5. Six regions in Iowa State

- **Pa**; Percent air voids in HMA mixture compacted in the laboratory

$$\text{Pa} = \left(1 - \frac{G_{mb,LAB}}{G_{mm,LAB}}\right) \times 100 = VTM_{LAB}$$

- **%Voids**; Percent air voids in HMA mixture compacted in the field

$$\%\ \text{Voids} = \left(1 - \frac{G_{mb,FIELD}}{G_{mm,LAB}}\right) \times 100 = VTM_{FIELD}$$

- **%Density**; Percent density, the ratio of bulk specific gravity of field-compacted mix to bulk specific gravity of laboratory-compacted mix

$$\%\ \text{Density} = \frac{Field\ \ Density}{G_{mb}\ (Lot\ Avg.)} \times 100 = \frac{G_{mb,FIELD}}{G_{mb,LAB}} \times 100$$

- **%AC**; Percent asphalt content by weight of total mix

- **FT** (microns); Film thickness, the thickness of the asphalt cement around aggregate

  Film Thickness (FT) = $\frac{P_{be}}{SA} \times 10$

- **F/B**; Fines to bitumen ratio, the ratio of $P_{\#200}$, the percentage by weight of the material passing #200 sieve (0.075μm) to effective asphalt content (P_{be}).

  F/B = $\frac{P_{200}}{P_{be}} \times 100 = \frac{P_{.075}}{P_{be}} \times 100$

- **VMA**; Voids in mineral aggregate, the total volume of voids including air voids and effective asphalt content expressed as a percentage of total volume between aggregates in the compacted HMA mix

  VMA = $\left\{1 - \frac{G_{mb,LAB}\left(100 - P_b\right)}{G_{sb}}\right\} \times 100$

- **VFA**; Voids filled with asphalt, the percentage of VMA volume filled with asphalt

  $VFA_{LAB} = \frac{VMA_{LAB} - P_a}{VMA_{LAB}} \times 100$

- **G_{mm}**; Maximum theoretical specific gravity of HMA mix, the ratio of the weight in air of a loose mix at a stated temperature to the weight of an equal volume of gas-free distilled water at a stated temperature
- **$\%G_{mm}$**; Percent theoretical maximum specific gravity of HMA mix

  %Gmm = $\frac{Field\ Density}{Gmm(Lot\ avg.)} = \frac{G_{mb,FIELD}}{G_{mm}}$

- **Aggregates gradations**; A single percentage by weight of aggregates passing each sieve size

In this study, significant outliers (α=0.05) in each grouped data were discarded before analyzing the data, using Grubbs' test (ASTM E 178–94, Standard Practice for Dealing With Outlying Observations [4]).

4.1 Percent Laboratory Air Voids (Pa)

Pa is expressed as a percentage of air voids in total volume of the laboratory-compacted HMA mix and it is also called VTM (voids in total mix). It has essentially the same meaning as %Voids, but Pa is determined from field laboratory-compacted specimens using the loose mix, whereas %Voids from sample cores (field-compacted mix) taken from the finished pavement. The following two equations used to calculate Pa and %Voids make this difference clear.

- Pa = $\left(1-\dfrac{G_{mb,LAB}}{G_{mm,LAB}}\right)\times 100 = VTM_{LAB}$
- % Voids = $\left(1-\dfrac{G_{mb,FIELD}}{G_{mm,LAB}}\right)\times 100 = VTM_{FIELD}$

Pa represents the volume of air voids in HMA pavement anticipated after a few years of service (traffic-compaction condition). It has been generally accepted that a HMA mixture should retain at least 3% during the life of the pavement to prevent rutting and shoving problems [5].

In Iowa DOT specification, there are three different target values (3.0, 3.5, 4.0) of Pa depending on the mix design method (Marshall and SUPERPAVE) and/or the traffic level of the project. Iowa DOT allows Pa variation up to 0.5% below and 1.0% above the target values. Pa values in the database were first, grouped by their targets and divided into regions, and then the target value was subtracted from Pa in DPR to examine its tolerance. The results are shown in Table 6.

4.2 Percent Field Air Voids (%Voids)

This percent air voids is, as pointed out above, the volume of air in HMA mix compacted by the roller in the field. These air voids should be initially larger than Pa and are designed such that normal traffic will induce secondary compaction, eventually to a state similar to Pa. Eight percent has been considered maximum as initial in-place voids (%Voids) to achieve low permeability of water and air; high voids (high permeability) result in water damage, oxidation, raveling, and cracking [5].

Table 6. Summary statistics of Pa

Target	Tolerance	Regions	Mean (DPR – Target)	Standard Deviation	Number of Samples
3.0	−0.5 / 1.0	**STATE**	**0.073**	**0.534**	**410**
		Central	N.A.[a]	N.A.	N.A.
		Northeast	0.004	0.451	127
		Northwest	0.017	0.410	103
		Southwest	0.219	0.673	162
		Southeast	0.275	0.395	4
		East Central	−0.231	0.661	16
3.5	−0.5 / 1.0	**STATE**	**0.059**	**0.519**	**1172**
		Central	N.A.	N.A.	N.A.
		Northeast	0.066	0.440	378
		Northwest	0.075	0.631	255
		Southwest	−0.044	0.492	340
		Southeast	0.370	0.500	47
		East Central	0.164	0.475	151
4.0	−0.5 / 1.0	**STATE**	**0.034**	**0.598**	**2569**
		Central	−0.070	0.551	320
		Northeast	0.126	0.575	324
		Northwest	0.049	0.776	192
		Southwest	0.047	0.536	919
		Southeast	0.202	0.675	345
		East Central	−0.079	0.506	462

[a] No data is in this region.

The tolerances of %Voids are specified as a range of 4.0% to 8.0% or 3.0% to 8.0%, depending on the mix type. As defined in I.M. 506, 507 and SPEC 4126, 4127, type A mix consists of high quality aggregates for carrying high traffic volumes like, ADT (Average Daily Traffic) greater than 5,000, while type B mix for low to moderate traffic. Summary statistics of %Voids are shown in Table 7.

4.3 Percent Density of Field Compacted Mixture (%Density)

Percent density, expressed as the ratio of $G_{mb,FIELD}$ to $G_{mb,LAB}$, represents the degree of field compaction compared with the laboratory-prepared specimen. Density, with voids criteria, is very important for ensuring the quality of HMA pavements and should be no less than the pre-specified %Density (94%, 95%, or 96%).

Table 7. Summary statistics of %Voids

Mix Type	Tolerance	Regions	Mean	Standard Deviation	Number of Samples
A	4.0 / 8.0	**STATE**	**6.821**	**0.966**	**824**
		Central	7.150	0.942	66
		Northeast	6.799	0.868	155
		Northwest	7.194	0.880	84
		Southwest	6.418	1.052	313
		Southeast	7.057	0.816	94
		East Central	7.227	0.729	114
B	3.0 / 8.0	**STATE**	**6.614**	**1.064**	**415**
		Central	N.A.[a]	N.A.	N.A.
		Northeast	6.236	0.903	87
		Northwest	7.169	0.991	122
		Southwest	6.257	1.001	108
		Southeast	5.945	0.769	22
		East Central	6.815	0.986	75

[a] No data is in this region.

Seven field densities ($G_{mb,FIELD}$) are measured from core samples each day, and are averaged. The deviation of measurements from target is also calculated to determine Q.I. (Quality Index) shown below the Density Record in DPR. Table 8 exhibits the summary statistics of %Density.

4.4 Percent Asphalt Content (%AC)

Asphalt content is expressed as a percentage by weight of total mix (P_b, percent binder), and a daily average amount of use is determined by stick measurements in the storage tank.

Table 8. Summary statistics of %Density

Target	Tolerance	Regions	Mean	Standard Deviation	Number of Samples
		STATE	**96.771**	**1.137**	**259**
		Central	-	-	1
		Northeast	97.438	1.102	69
94%	Minimum	Northwest	96.125	0.891	89
		Southwest	97.136	0.803	33
		Southeast	94.545	3.392	5
		East Central	96.822	1.053	53
		STATE	**96.846**	**0.897**	**821**
		Central	96.639	0.803	64
		Northeast	96.734	0.778	130
95%	Minimum	Northwest	96.262	0.784	126
		Southwest	97.243	0.876	264
		Southeast	97.110	0.865	114
		East Central	96.508	0.638	120
		STATE	**97.563**	**0.775**	**172**
		Central	-	-	1
		Northeast	97.554	0.565	43
96%	Minimum	Northwest	N.A.[a]	N.A.	N.A
		Southwest	97.591	0.839	123
		Southeast	N.A.	N.A.	N.A.
		East Central	96.853	0.408	5

[a] No data is in this region.

The amount of asphalt added or sprayed evenly to aggregates should be enough to coat the aggregate properly, but not too much, because it can lubricate the friction of aggregates thereby reducing the stability of the mixture [6]. %AC also effects the other volumetric properties of HMA mix such as, film thickness, F/B ratio, VMA, and VFA. For a given aggregate blend, the appropriate amount of asphalt is determined to provide the mixture with specified air voids when JMF is developed, and during production, this should conform to JMF value as a target within ± 0.3%.

The difference of the actual (tank-stick) %AC from its target was calculated first, and analyzed to obtain the results in Table 9.

4.5 Film Thickness (FT)

Film thickness is estimated in microns using the effective asphalt content (P_{be}) and the surface area of aggregate determined by multiplying surface area factors by the percentage of aggregate passing each sieve size. Even though it is unlikely that all the particles in a mix have the same FT, for the purpose of calculation, average film thickness concept is considered valid or useful, and it is believed that sufficient FT around the aggregate is essential for the durability of HMA pavement performance [7].

Table 9. Summary statistics of %AC

Target	Tolerance	Regions	Mean (JMF – DPR)	Standard Deviation	Number of Samples
JMF	–0.3 / +0.3	**STATE**	**–0.013**	**0.118**	**1583**
		Central	–0.026	0.087	105
		Northeast	–0.023	0.114	288
		Northwest	–0.010	0.129	275
		Southwest	–0.009	0.132	512
		Southeast	–0.004	0.109	145
		East Central	–0.011	0.071	253

Specified ranges of FT are 7.5 to 13.0 and 8.0 to 13.0 microns depending on the layer where the mix placed. To evaluate the production conformity to JMF, the deviation from its target described in JMF, (JMF – DPR), was also calculated, and Table 10 summarizes the results.

4.6 Fines to Bitumen Ratio (F/B Ratio)

Fines (filler) to bitumen ratio called dust proportion in SUPERPAVE stands for the ratio of $P_{\#200}$, the percentage by weight of the material passing #200 sieve (0.075μm) to effective asphalt content (P_{be}). $P_{\#200}$ is determined from cold feed gradations and the amount of fines in the HMA mixture should be regulated to control the voids-related properties of the mix. Appropriate amount of fines in HMA mixes increases the density and strength of the compacted mixture and the viscosity of the binder, thereby increasing rutting resistance of HMA pavement [8].

Table 10. Summary statistics of Film Thickness

Target	Tolerance	Regions	Mean	Standard Deviation	Number of Samples[a]
-	7.5,8.0 / 13.0	**STATE**	**9.665**	**1.372**	**1387**
		Central	9.652	1.436	66
		Northeast	9.400	1.200	263
		Northwest	9.007	1.314	243
		Southwest	10.093	1.328	478
		Southeast	9.196	1.229	130
		East Central	9.997	1.180	203
			(JMF–DPR)		
JMF	-	**STATE**	**1.496**	**1.616**	**736**
		Central	0.614	1.178	63
		Northeast	0.411	1.185	91
		Northwest	1.182	1.413	115
		Southwest	2.053	1.650	409
		Southeast	1.048	0.639	38
		East Central	0.335	1.097	19

It also has been known that more fines are generated during production due to abrasion. Currently Iowa DOT sets its tolerance as the range of 0.6 to 1.4. All F/B ratio values in DPR were averaged by state-basis and region-basis, and the deviation from JMF target was also calculated to compare the production conformity (Table 11).

4.7 VMA

The total volume of voids including air voids and effective asphalt content expressed as a percentage of total volume, between aggregates in the compacted HMA mix is designated VMA (voids in mineral aggregate), and is one of the most critical criteria in mix design. Also during production, VMA should be monitored to achieve proper film thickness and air voids in the mixture so that HMA pavement resists to stability and durability problems [3, 6].

Table 11. Summary statistics of Fines to Bitumen Ratio

Target	Tolerance	Regions	Mean	Standard Deviation	Number of Samples
-	0.6 / 1.4	**STATE**	**0.850**	**0.187**	**1469**
		Central	0.839	0.163	73
		Northeast	0.868	0.205	284
		Northwest	0.790	0.136	271
		Southwest	0.886	0.173	490
		Southeast	0.981	0.270	140
		East Central	0.750	0.126	213
			(JMF–DPR)		
JMF	-	**STATE**	**–0.124**	**0.156**	**901**
		Central	–0.044	0.135	72
		Northeast	–0.069	0.132	94
		Northwest	–0.107	0.137	252
		Southwest	–0.163	0.165	417
		Southeast	–0.176	0.139	40
		East Central	–0.024	0.103	26

Statistical analysis of this factor was performed in two ways. First, VMA records in DPR (VMA_{LAB}) were analyzed and second, its difference from target ($VMA_{JMF} - VMA_{LAB}$) was analyzed as shown in Table 12, to check its production variations. It should be noted that while VMA_{LAB} is shown on the right-hand side of the DPR, it is calculated using the information obtained from the left-hand side of the same page.

4.8 VFA

No tolerances are specified for the VFA (voids filled with asphalt) that is the percentage of VMA volume filled with asphalt. Since VFA does not appear in DPR, all values were calculated based on the volumetric data on the DPR of the day. Statistical analysis of VFA factor was performed as the same ways as those of VMA and the following formula was used to calculate each VFA.

Table 12. Summary statistics of VMA_{LAB}

Target	Tolerance	Regions	Mean	Standard Deviation	Number of Samples
-	-	**STATE**	**14.746**	**1.007**	**1221**
		Central	13.518	0.491	13
		Northeast	14.969	1.069	222
		Northwest	15.249	0.845	257
		Southwest	14.500	0.936	446
		Southeast	14.422	1.009	88
		East Central	14.598	0.934	194
			(JMF–LAB)		
JMF	-	**STATE**	**0.844**	**0.954**	**732**
		Central	1.482	0.871	12
		Northeast	–1.126	0.891	42
		Northwest	1.035	0.696	230
		Southwest	1.038	0.805	384
		Southeast	0.002	0.566	38
		East Central	0.742	0.532	23

- $\text{VFA}_{\text{LAB}} = \dfrac{VMA_{LAB} - P_a}{VMA_{LAB}} \times 100$

Table 13 shows the results of this analysis.

4.9 Theoretical Maximum Specific Gravity (Gmm and %Gmm)

Gmm denotes theoretical maximum specific gravity of HMA mix measured using the loose mix and this is also called TMD (theoretical maximum density) or Rice density. %Gmm, the percent TMD, is the ratio of bulk density of the mix to the Gmm. In this study, Gmm(Lot Avg.) below the Density Record in DPR was used and %Gmm was calculated individually as follows:

- $\%\text{Gmm} = \dfrac{Field\ Density}{Gmm(Lot\ avg.)} = \dfrac{G_{mb,FIELD}}{G_{mm}}$

Table 13. Summary statistics of VFA_{LAB}

Target	Tolerance	Regions	Mean	Standard Deviation	Number of Samples
-	-	**STATE**	**74.127**	**4.250**	**1220**
		Central	73.799	4.462	13
		Northeast	75.092	4.190	221
		Northwest	75.646	4.627	257
		Southwest	73.400	3.882	443
		Southeast	71.296	3.552	88
		East Central	73.809	3.100	194
			(JMF–LAB)		
JMF	-	**STATE**	**1.757**	**3.228**	**727**
		Central	0.291	3.678	12
		Northeast	−0.573	1.544	41
		Northwest	2.280	3.499	233
		Southwest	1.901	2.891	377
		Southeast	1.497	2.272	37
		East Central	−0.497	3.532	23

%Gmm(Lab) used in SUPERPAVE mix design to determine the optimum asphalt content providing 4% air voids is different from %Gmm(Field) analyzed here, and this is another way to check the compaction effort during construction, because the voids of the field-compacted mixture, %Voids = (1 – %Gmm) × 100. The results of Gmm and %Gmm are shown in Table 14 and 15, respectively.

4.10 Aggregate Gradations

Aggregate selection and their blends are the first step in mix design and the control of gradations to consistently conform to the JMF target is crucial to the quality of the final products.

Table 14. Summary statistics of Gmm

Target	Tolerance	Regions	Mean	Standard Deviation	Number of Samples
		STATE	**2.460**	**0.042**	**1401**
		Central	2.487	0.044	68
		Northeast	2.449	0.028	265
-	-	Northwest	2.446	0.037	248
		Southwest	2.452	0.024	480
		Southeast	2.447	0.061	131
		East Central	2.511	0.039	209

Table 15. Summary statistics of %Gmm

Target	Tolerance	Regions	Mean	Standard Deviation	Number of Samples
		STATE	**93.234**	**1.035**	**1254**
		Central	92.851	0.930	66
		Northeast	93.412	0.937	242
-	-	Northwest	92.723	0.935	217
		Southwest	93.619	1.044	421
		Southeast	93.138	0.961	117
		East Central	92.917	0.830	188

It has been reported that the type of aggregate and its gradation has significant effects on volumetric properties, including VMA and %AC of HMA mixture [9, 10] and the performance of the HMA pavement [11]. Table 16 and 17 exhibit summary statistics of aggregate gradation of mix type A and B.

Table 16. Summary statistics of Mix Type A - Gradations

Sieve Size	Target	Tolerance	Regions	Mean (JMF-DPR)	Standard Deviation	Number of Sample
			STATE	**–0.251**	**2.754**	**929**
			Central	0.540	2.610	104
			Northeast	–1.180	2.120	135
#4	JMF	–7 / +7	Northwest	–0.190	2.910	125
			Southwest	–1.051	2.731	311
			Southeast	0.600	2.366	100
			East Central	0.951	2.581	152
			STATE	**–0.270**	**2.435**	**935**
			Central	0.962	2.288	106
			Northeast	–0.510	2.110	136
#8	JMF	–5 / +5	Northwest	–0.722	2.643	126
			Southwest	–0.887	2.293	313
			Southeast	0.790	2.138	100
			East Central	0.032	2.355	152
			STATE	**–0.925**	**1.606**	**932**
			Central	–0.613	1.405	106
			Northeast	–0.600	1.410	136
#30	JMF	–4 / +4	Northwest	–1.240	1.948	126
			Southwest	–1.360	1.567	310
			Southeast	–0.540	1.487	100
			East Central	–0.582	1.426	153
			STATE	**–0.412**	**0.627**	**934**
			Central	–0.002	0.593	106
			Northeast	0.643	0.444	137
#200	JMF	–2 / +2	Northwest	–0.513	0.753	126
			Southwest	–0.389	0.664	312
			Southeast	–0.766	0.480	100
			East Central	–0.206	0.427	153

Table 17. Summary statistics of Mix Type B - Gradations

Sieve Size	Target	Tolerance	Regions	Mean (JMF-DPR)	Standard Deviation	Number of Sample
			STATE	**−0.560**	**3.014**	**598**
			Central	-	-	1
			Northeast	−0.360	2.410	121
#4	JMF	−7 / +7	Northwest	−0.241	3.178	162
			Southwest	−1.980	2.490	156
			Southeast	−0.706	2.886	51
			East Central	0.924	2.916	105
			STATE	**−0.351**	**2.624**	**596**
			Central	-	-	1
			Northeast	0.721	1.976	122
#8	JMF	−6 / +6	Northwest	−0.154	2.929	162
			Southwest	−1.900	2.320	156
			Southeast	−0.275	1.981	51
			East Central	0.393	2.463	104
			STATE	**−0.480**	**1.880**	**598**
			Central	-	-	1
			Northeast	0.303	1.636	122
#30	JMF	−5 / +5	Northwest	−0.660	2.255	162
			Southwest	−0.860	1.770	157
			Southeast	−0.627	1.562	51
			East Central	−0.467	1.557	105
			STATE	**−0.283**	**0.642**	**599**
			Central	-	-	1
			Northeast	−0.397	0.680	122
#200	JMF	−3 / +3	Northwest	−0.192	0.498	161
			Southwest	−0.093	0.688	158
			Southeast	−0.992	0.580	51
			East Central	−0.282	0.385	103

CHAPTER 5. ANALYSIS AND DISCUSSION

Eleven factors have been investigated in this analysis, however, only seven of these are currently subject to tolerance or other limits by the DOT. The statistics and variabilities measured on these extra four factors have been provided at the request of the IDOT for their own purposes. The analyses performed and reported in this chapter pertain only to those factors that are subject to tolerance or other specification limitations.

There are four major objectives of this study:

1. to examine specification tolerances and limitations for reasonableness,
2. to identify and report significant departures from statistical normality, and
3. to identify and report any significant regional differences in compliance, and
4. to make recommendations to correct any deficiencies found, or to suggest alternate QC/QA procedures

5.1 Tolerances

Current practice suggests that tolerance should be set to permit only a 5% rejection, or at ± 1.96 standard deviations from the mean for two-sided limits and at 1.64 standard deviations from the mean for one-sided limits. This allows an examination of the reasonableness of current IDOT tolerances. Since this project has measured actual production variability for each factor from the records provided, if the variabilities observed are less than the values quoted above, then contractors are capable of meeting current requirements. If, on the other hand, there is a larger than 5% rejection rate observed, contractors are at enhanced risk of rejection. The suggestion might be to further examine the current tolerance specification with a view to enlarging the tolerance band to achieve a more reasonable rejection rate. In the following Table 18, each factor so far considered is examined with respect to the statistical rejection rate.

This analysis indicates that, under current specifications, contractors are meeting required tolerances for all factors with the exception of Pa and FT. In fact, it can be shown that none of the district or regional data met tolerance for Pa at the 5% rejection level.

Table 18. Examination of specified tolerance ranges with 5% rejection rate

Factors	Target / Mix type	Tolerance Range	2×1.96× (Measured Standard Deviation)	Remark
Pa	3.0	1.5	2.09	Out of range
	3.5	1.5	2.03	Out of range
	4.0	1.5	2.34	Out of range
%Voids	A	4.0	3.79	O.K.
	B	5.0	4.17	O.K.
%AC	–	0.6	0.46	O.K.
FT	Wearing course	5.0	5.38[a]	Out of range
	Non-wearing course	5.5	5.38[a]	O.K.
F/B ratio	–	0.8	0.73	O.K.
Gradations	A / #4	14.0	10.80	O.K.
	A / #8	10.0	9.55	O.K.
	A / #30	8.0	6.30	O.K.
	A / #200	4.0	2.46	O.K.
	B / #4	14.0	11.81	O.K.
	B / #8	12.0	10.29	O.K.
	B / #30	10.0	7.37	O.K.
	B / #200	6.0	2.52	O.K.

[a] Since course-differentiation was ignored in this study, this was calculated using the same statewide standard deviation of FT.

The problem with air voids, Pa, may lie in the fact that the target air void is not centrally located within the tolerance band. This is confirmed with reference to Figure 6 in the following section, which clearly shows that the distributions for Pa are distinctly non-normal. This could be addressed by either (a) removing the target air void requirement and keeping the tolerance range, or (b) by altering the distribution of the tolerance range about the target value.

The Film Thickness, FT, factor is shown to be marginally at increased risk of rejection. This latter is confounded by the infinity of gradations represented, which taken with the conceptual method for computing this parameter, make the calculated magnitudes somewhat sensitive to minor variations in the gradation – more particularly in the finer sieve sizes. Since FT is a function of both aggregate gradation (through surface area, SA) and effective binder content, P_{be}, it can be considered a useful check that variations in these other factors within their own tolerances do not combine to give a "bad" mixture. For example, a binder content at its lowest acceptable limit combined with an aggregate at its highest tolerable value (fine graded aggregate) can, in the aggregate, provide a lean, dry mixture with unacceptable properties, and reduced durability.

Table 18 above, considers only those factors with both upper and lower tolerance limits. However, the %Density factor requires only a one-sided tolerance; the only requirement is that the compacted mixtures exceed the required minimum %Density. In the interests of fairness and equity, the rejection rate should be examined to determine whether the contractors are having difficulty in meeting this standard (Table 19). In this case, if the observed mean value exceeds the specified minimum value by more than 1.64σ, then the rejection risk is less than 5%.

Table 19. Acceptance/rejection of %Density at 5% rejection rate

Target	Regions	Mean	Standard Deviation	Number of sample	μ - 1.64σ	Accept/Reject
	STATE	**96.771**	**1.137**	**259**	**94.9**	**Accept**
	Central	-	-	1	-	-
	Northeast	97.438	1.102	69	95.6	Accept
94%	Northwest	96.125	0.891	89	94.7	Accept
	Southwest	97.136	0.803	33	95.8	Accept
	Southeast	94.545	3.392	5	89.0	Reject
	East Central	96.822	1.053	63	95.1	Accept
	STATE	**96.846**	**0.897**	**821**	**95.4**	**Accept**
	Central	96.639	0.803	64	95.3	Accept
	Northeast	96.734	0.778	130	95.5	Accept
95%	Northwest	96.262	0.784	126	95.0	Accept
	Southwest	97.243	0.876	264	95.8	Accept
	Southeast	97.110	0.865	114	95.7	Accept
	East Central	96.508	0.638	120	95.5	Accept
	STATE	**97.563**	**0.775**	**172**	**96.3**	**Accept**
	Central	-	-	1	-	-
	Northeast	97.554	0.565	43	96.6	Accept
96%	Northwest	N.A.[a]	N.A.	N.A.	N.A.	N.A.
	Southwest	97.591	0.839	123	96.2	Accept
	Southeast	N.A.	N.A.	N.A.	N.A.	N.A.
	East Central	96.853	0.408	5	96.2	Accept

[a] No data is in this region.

The only district results indicating rejection is the Southeast District at the 94% Density level. However, since there are only five (5) results in this district, it is not felt that this result is significant. Otherwise, there is little or no indication that the minimum density requirement is posing any difficulty for the contractors.

This simplified analysis is based on the symmetrical distribution of data known as the Normal or Gaussian distribution. Other distributions would imply that the normalized range, 2 x 1.96σ would no longer apply, and some other measure defining a

5% rejection range would apply. This is investigated in section 5.2 below.

5.2 Distributional Characteristics of Data

It should be noted that the test results used in statistical calculations are not the 'population' but 'samples' taken from the populations. To represent the population, as a prerequisite, the sampling should be random, and 'Probability' concept needs to be applied before making inferences about the population that involves at least three features of the data: mean, standard deviation, and distribution. To properly infer the population of the project data used in this study, and eventually to evaluate the construction quality of the projects, the distributions of volumetric and other density properties need to be reviewed. First, Frequency Histograms, the most common method in statistics to approximate the distribution of data, were used for this purpose. The range of the data (the difference between the largest and the smallest data) was divided by appropriate number of class intervals, and each interval's frequency was counted to construct the frequency table and frequency histogram.

It is worth mentioning that, even though the frequency histogram is simple and easy, it has drawbacks in estimating the distribution of given data. Since the number of cells (intervals) has an effect on the outline of the frequency distribution, and it tends to more regular the smaller the number of cells [12], it is recommended that the number of cells in a frequency distribution be between 13 and 20, and the cell boundaries be chosen half-way between two possible observations [13].

Since it has been assumed that the distributions of data are normally distributed, frequency histograms of some factors were drawn with the appropriate normal curve superimposed, $N(\mu, \sigma^2)$, as shown in Figure 6.

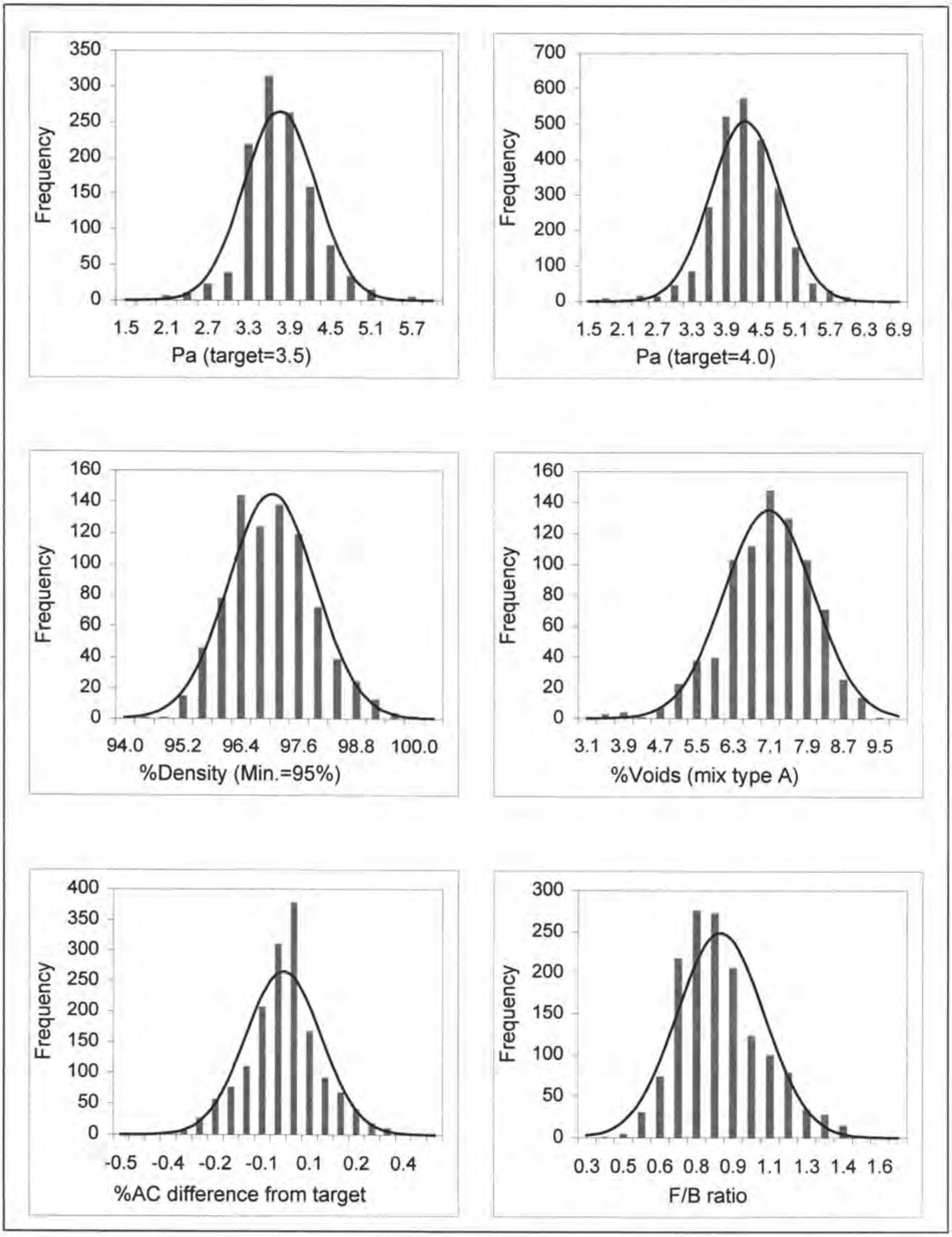

Figure 6. Distributions of the factors (Statewide)

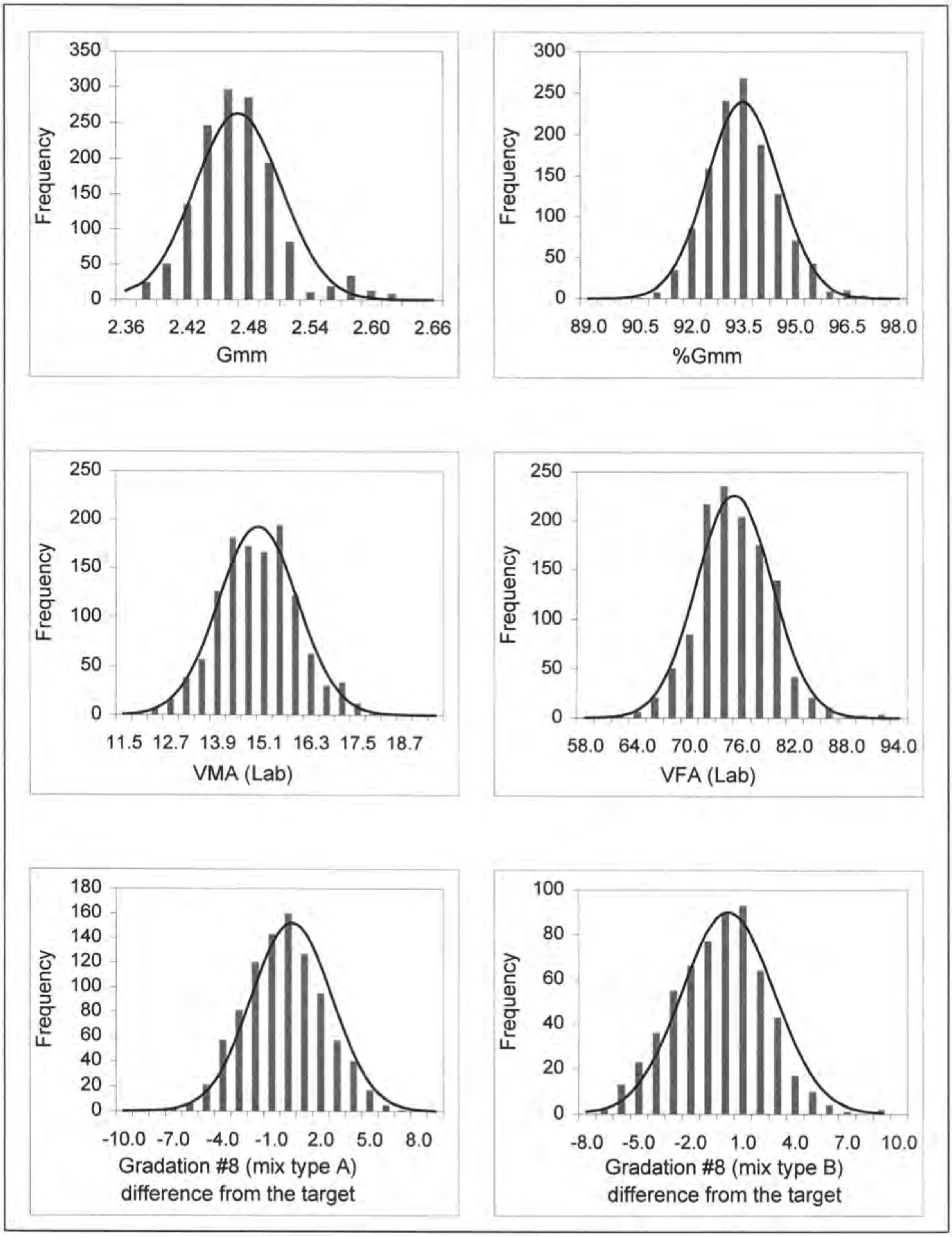

Figure 6. (continued)

The distributions of the factors, as seen in the sub-figures, are generally bell-shaped or mound-shaped, like normal probability distribution curves. However, there was a concern that these factors are truly normally distributed or at least, the populations describing them could be modeled by normal distribution. The theoretical normal probability distribution shown in Figure 7, has several distinctive characteristics as follows [14, 15]:

- Bell-shaped
- Unimodal (one peak), Kurtosis (peakedness) = 3.0
- Symmetrical about the mean (μ), Skewness (lopsidedness) = 0.0
- Asymptotic to the abscissa
- The density function, $f(y) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(y-\mu)^2/2\sigma^2}$
- 95% of the total area between the curve and the abscissa (95% probability) lies in the interval $\mu \pm 1.96\sigma$

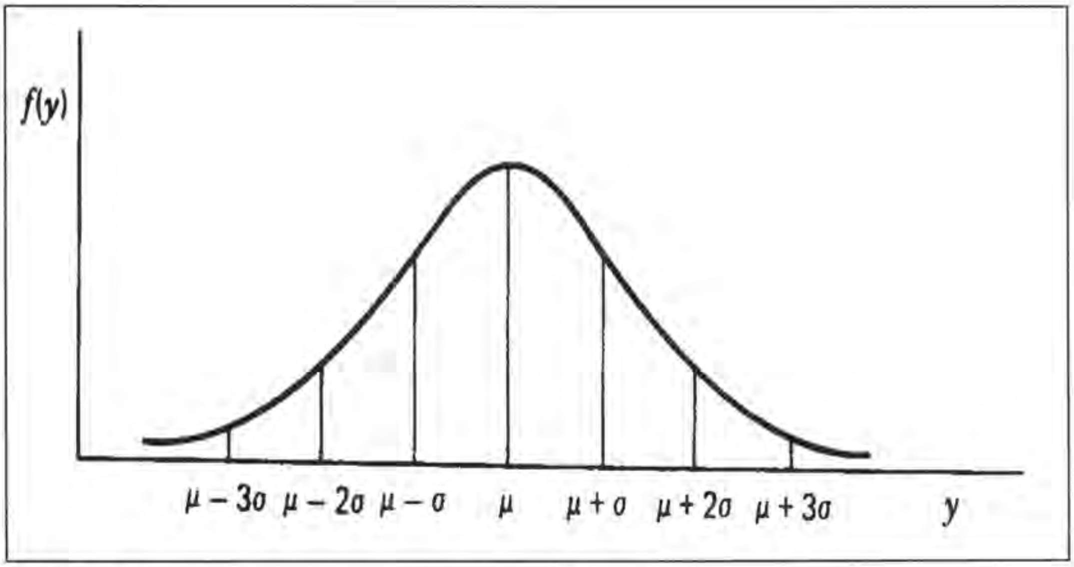

Figure 7. The normal distribution, N (μ, σ^2)

Comparing the histogram distributions with the superimposed normal distribution curves, it can be seen, that in general, the characteristics of normality are not strongly violated. Some differences, however, are observed with respect to kurtosis and skewness. Most of the distributions of the data show relatively high and sharp peaks around their means and existence of the extreme values. These latter could be explained by the fact that production during the first few days is not stable, while thereafter the products are closely controlled and manipulated to be close to their targets, through continuous monitoring and testing.

There are semi-quantitative or quantitative methods being used to check the suitability of the model. These candidate methods are the Normal Probability Plot (Q-Q plot, sample quantiles vs. normal quantiles), Goodness-of-Fit tests using Chi-Square (χ^2) distribution and Kolmogorov-Smirnov method [16, 17].

Once the shape of the distribution of the observed data is examined by a stem-leaf, a dot plot, or frequency histogram, further investigation is possible by Q-Q plot (Figure 8).

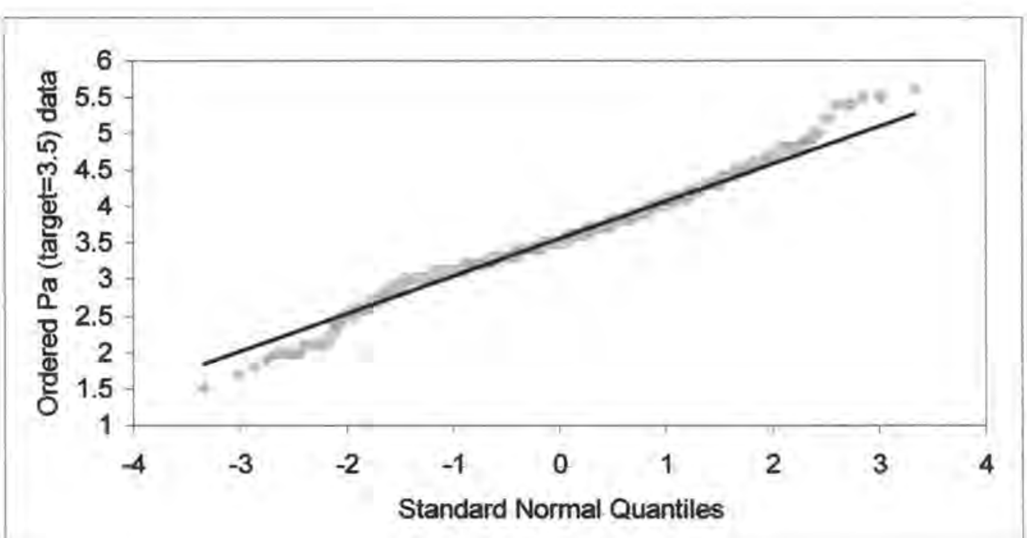

Figure 8. Normal probability plot using Pa data (target=3.5, n=1172)

If the distribution resembles a normal distribution the plotted points will lie in a fairly straight line. On the other hand, the non-linearity of the plot indicates that a normal distribution may not be an appropriate model. Generally, graphical methods are simple and can be performed easily to determine whether the data conforms to a hypothesized distribution, but deciding the linearity is based on a subjective visual examination.

Goodness-of-fit tests using chi-square distribution and Kolmogorov-Smirnov method are based on more or less similar principle: comparing the observed frequencies with the corresponding (expected) frequencies from an assumed probability distribution.

Although those two tests are widely used to validate statistically whether the given data can be modeled by the assumed theoretical probability distributions, it is somewhat arbitrary to choose the magnitude of frequency intervals and the significance level (α), which have significant effect on the appraisal of the goodness-of-fit.

Kolmogorov-Smirnov test was performed on the F/B ratio data as shown in Figure 9, and the result was less than 0.001, which indicates a very poor fit; the better the model, the closer to 1.0.

One thing should be mentioned, here, is that the assumption of normal distribution is very powerful tool and widely used in many fields including engineering, to statistically analyze the data, and statistics allows the normal distribution to play an important role 'safely' when making inferences about a population, by a supportive theory, Central Limit Theorem. This critical theory says that if an underlying population is normal, the sample distribution is normal, and if not, the sample distribution is 'approximately' normally distributed for sufficiently large samples (conventionally, more than 30) [14, 18].

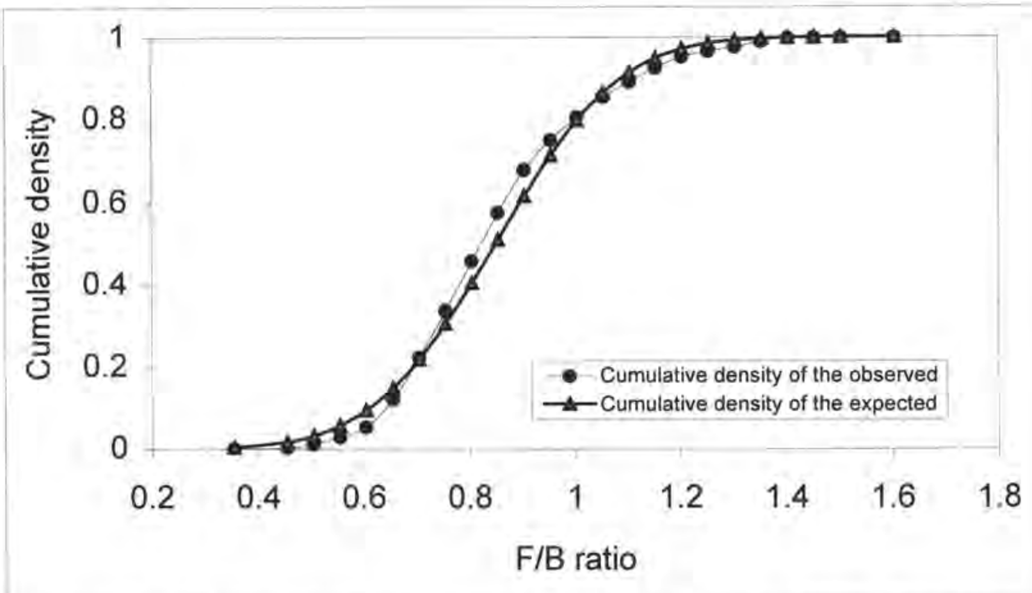

Figure 9. Kolmogorov-Smirnov test using F/B ratio data (n=1469)

The major purpose of identifying the distribution of the data is for making an inference about the population; i.e. especially in this study, predicting the Percent Within Limits (PWL) and/or the 'Confidence Interval' for the calculated mean and standard deviation of each factor. PWL should be correctly estimated to evaluate the production quality. For this purpose, Table 20 was prepared. Under the assumption of the normal distribution, the data were normalized to the standard normal distribution, N(0,1), and their PWL was calculated. To examine the estimated PWL based on normal distribution, each single value of the data was reviewed again and the value within the tolerance was counted. As shown in Table 20, PWLs obtained from two methods show large differences on some of the factors. These discrepancies indicate that the assumption of normal distribution of the data might not be appropriate for estimating PWL.

Table 20. Estimated PWL vs. actual data counting

Factors		Tolerance		Mean (μ)	Standard deviation (σ)	PWL (%)	
		Lower limit	Upper limit			Estimated by normal distribution	By actual data counting
Pa	Target 3.0	2.5	4.0	3.10	0.58	81.71	87.32
	Target 3.5	3.0	4.5	3.56	0.54	82.44	89.33
	Target 4.0	3.5	5.0	4.03	0.62	76.10	85.17
%Voids	Mix type A	4.0	8.0	6.82	1.01	99.94	91.14
	Mix type B	3.0	8.0	6.65	1.16	99.97	91.33
%Density	Target 94%	94.0		96.71	1.27	> 99.99	99.61
	Target 95%	95.0		96.85	0.93	> 99.99	99.51
	Target 96%	96.0		97.56	0.78	> 99.99	98.84
%AC difference form target		–0.3	+0.3	–0.01	0.14	98.85	98.48
F/B ratio		0.6	1.4	0.86	0.22	90.77	94.96

In the above table, it can be seen that the failure rates of Pa, %Voids and perhaps the F/B ratio are not in agreement with the normal model. Without regard to the validity of normal distribution or other theoretical distributions to the production data, there is another possible way to approximate PWL. Since cumulative density function (CDF) of the data, instead of considering probability distribution function (PDF), is curvilinear shaped like a tilted *S*, and CDF can be formularized like below:

- $\mathrm{P(x)} = \dfrac{\exp(\phi)}{1+\exp(\phi)}$

This function is called 'logistic function' [19], and can easily be linearized, using natural logarithm transformation:

- $\phi = \ln\left(\dfrac{P(x)}{1-P(x)}\right)$

'ϕ' can be any kind of function of x, and a linear (or polynomial) regression is applicable. Generally, selecting the best regression model is not simple, and various statistical methods are needed to find the best, e.g., backward elimination, stepwise regression, and so on [20]. However, since there is only one independent variable, the regression model for the data used in this study can easily be found using Analysis of Variance (ANOVA) with R^2 (coefficient of correlation). An example is shown Figure 10, and further inferences about the population can be made based on the regression model.

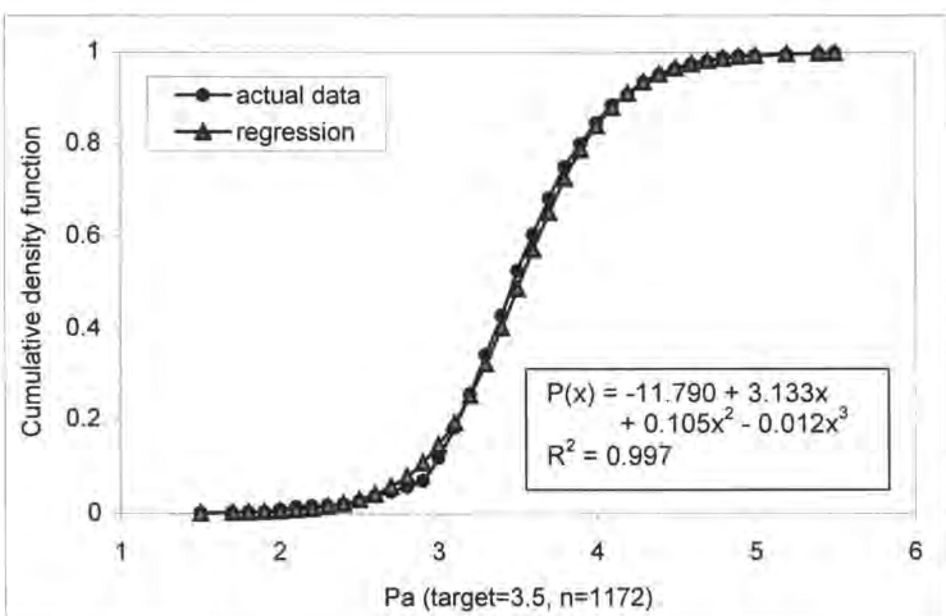

Figure 10. CDF regression using 'Logistic Function'

This method allows the researcher to establish "non-Gaussian" distributions from quasi-population statistics. The DOT is considering a transition to Percent-within-Limits (PWL) specifications. If the underlying population distribution can be considered as representative and stable, then this method would provide a means by which tabular probability values could be generated in much the same way as is currently available for normal, or Gaussian, distributions.

5.3 Regional Differences

As a sub-task of this study, regional differences about the volumetric and other density factors of HMA mix were examined. This possibility was justified by the fact that the aggregates mixed with asphalt have different properties, depending on the local geology and production equipment so that it affects the properties of the products.

To test this distinct possibility, statistical comparison methods were employed in two different ways: pairwise comparisons, and multiple comparisons.

As pairwise comparison method, the most common and simple approach to compare two means is 't-test'. Under the assumption that each population is normal, the difference of two means is hypothesized as '0' ($H_o : m_1 - m_2 = 0$), and the hypothesis is rejected or accepted by comparing the calculated t-statistic using the combined variances from the two samples, with the t-value in Student's t distribution table at a given level of type I error (α) and degree of freedom (df or ν). The pooled t-test is used when the variances and the sample sizes of two samples are approximately equal. As an alternative, the separate-variance t-test (t'-test) is used for the other case. Selecting one of these two methods is dependent on the result of F-test (s_1^2/s_2^2).

The multiple comparisons methods are considered when more than two samples are compared. The t-test can be used also, by comparing all possible pairs of the samples. The problem, however, related to using t-test in multiple comparisons is that as the number of comparison increases, the error rate increases together. It is believed that comparing 6 sample-means (15 pairs) using t-test, generates $1 - (1 - 0.05)^{15} = 0.54$ error rate, when each pair is compared with 0.05 type I error (95% confidence); the result is correct with 46% confidence. Thus, it is suggested that a significantly small value of α should be applied to each comparison when t-test is used. However, when a sufficiently small α, like 0.001 or 0.0005, is used, any difference of two samples cannot be detected [18]. In multiple comparisons, instead of controlling comparisonwise type I error, the overall type I error rate (experimentwise error) is controlled within a given α level using the common variance for all samples obtained from ANOVA analysis, instead of the common variance for two samples compared in t-test.

In this study, three procedures were used to compare the means:

- t-test (or t'-test)
- Fisher's Least Significant Difference (LSD)
- Tukey's W procedure

All of the three methods are very popular in many fields. LSD is known as a common one in engineering, and Tukey's W is the most conservative.

Table 21 shows the test results of these methods, as an example using Pa factor, and no significant differences about the statistical methods are observed. More importantly, Table 21 indicates that statistical comparison-techniques are so sensitive to the sample variance and size that every pair is differentiated as being difference.

Comparisons about the population variances are shown in Table 22, using F-test, and the useful applications of this test are discussed in the following section 5.4.

Table 21. Comparing population means (Pa; target=4.0), α=0.05

Pa (target=4.0)		Northeast	Northwest	Southwest	Southeast	East Central
Central	t-test	*[a]		*	*	
$\mu = 3.930$, $\sigma = 0.551$	LSD	*	*	*	*	
n = 320	Tukey	*		*	*	
Northeast	t-test			*		*
$\mu = 4.126$, $\sigma = 0.575$	LSD			*		*
n = 324	Tukey					*
Northwest	t-test				*	*
$\mu = 4.049$, $\sigma = 0.776$	LSD				*	*
n = 192	Tukey				*	
Southwest	t-test				*	*
$\mu = 4.047$, $\sigma = 0.536$	LSD				*	*
n = 919	Tukey				*	*
Southeast	t-test					*
$\mu = 4.202$, $\sigma = 0.675$	LSD					*
n = 345	Tukey					*
East Central	t-test					
$\mu = 3.921$, $\sigma = 0.506$	LSD					
n = 462	Tukey					

[a] * denotes that two means in the pair are different.

Table 22. F-test for comparing population variances (Pa; target=4.0), α=0.05

Pa (target=4.0)	Central	Northeast	Northwest	Southwest	Southeast	East Central
State $\sigma = 0.598$			*[a]	*	*	*
Central $\sigma = 0.551$			*		*	
Northeast $\sigma = 0.575$			*		*	*
Northwest $\sigma = 0.776$				*	*	*
Southwest $\sigma = 0.536$					*	
Southeast $\sigma = 0.675$						*
East Central $\sigma = 0.506$						

[a] * denotes that two variances in the pair are different.

5.4 Discussion

It has been shown that under current specification tolerances, only Pa is seriously at risk of rejection at a level exceeding 5%. This conclusion is general throughout the state. It has been further shown that while the normal distribution may be accepted as a fair model of the data for most factors, it is not a good predictor for Pa. It has also been shown, at least statistically, that factor variabilities between regions are different, and that the district variabilities are not statistically the same as that for the state as a whole.

The problem with the Pa compliance rests in the specification of a target mean, and an unsymmetrical tolerance range. This could be addressed by the DOT by either (a) adjusting and making the tolerance range symmetric about the target mean, or by (b) setting only the upper and lower limits of tolerance and abandoning the target mean requirement.

The Iowa DOT is considering moving forward to a Percent within Limits (PWL) specification. This will require an assurance that the underlying data distributions are normally distributed, or where that assumption cannot be made to sufficiently define the parent distribution and prepare tables based on its properties. It has been shown that this can be done using the Logistic Curve approach.

In setting acceptability limits (tolerances) for a PWL specification, the DOT must take care to set limits that are fair and do not disadvantage any districts within the state. Since the 5% rejection level is routinely adopted as a fair measure, tolerance limits should be set at $\mu \pm k\sigma$, in which case the state may arbitrarily set the target (μ), but must judiciously chose the statewide standard deviation (σ) such that all districts can reasonably expect to meet the requirement at the 5% rejection level.

The following Table 23 shows how the statewide standard deviations may have to be adjusted to allow each district to meet a 5% rejection level, using F-test. The adjustment is minor in most cases, and in any case, the DOT is likely to round up such number to make sensible numbers for publication in the specification. In many cases, the statewide standard deviations may not need to be adjusted to bring districts into compliance.

Table 23. The adjusted statewide standard deviation of each factor

Factor	Target / Mix type	Measured Standard deviation	Adjusted[a] Standard deviation
Pa	3.0	0.534	0.594
	3.5	0.519	0.575
	4.0	0.598	0.703
%Voids	A	0.966	0.966 / 0.962[b]
	B	1.064	1.064 / 0.909[b]
%Density	94	1.137	1.137[c] / 0.931[b,c]
	95	0.897	0.897 / 0.811[b]
	96	0.775	0.775 / 0.714[b]
%AC	JMF	0.118	0.123
FT	-	1.372	1.372 / 1.221[b]
F/B	-	0.187	0.240
Gmm	-	0.042	0.054
%Gmm	-	1.035	1.035 / 0.967[b]
VMA	-	1.007	1.007 / 0.970[b]
VFA	-	4.250	4.250 / 4.219[b]
Gradations of aggregate	JMF / A / #4	2.754	2.754 / 2.566[b]
	JMF / A / #8	2.435	2.435 / 2.331[b]
	JMF / A / #30	1.606	1.718
	JMF / A / #200	0.627	0.627 / 0.664[b]
	JMF / B / #4	3.014	3.014 / 2.822[b]
	JMF / B / #8	2.624	2.624 / 2.601[b]
	JMF / B / #30	1.880	2.002
	JMF / B / #200	0.642	0.642 / 0.611[b]

[a] State standard deviation adjusted to permit all regions equal chance at 5% level of significance

[b] possible reduction limit of State standard deviation to permit all regions equal chance at 5% level significance

[c] Southeast region was excluded in consideration for small number of sample (n=5)

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Tolerances

An examination of project records over the last two to three years indicates that contractors are quite able to produce and place HMA mixtures within currently specified tolerances, with the exception of those for laboratory compacted loose mix sample's Pa. The tolerances for this factor are unusual insofar as they require both a target value and a symmetrical tolerances band. Based on the statistics of the collected data, the rejection rate for Pa is of the order of ten to fifteen percent, while normal practice admits a rejection rate of 5%. It is recommended that DOT consider the following possible corrective action:

1. retain the upper and lower limits on Pa, while relaxing the requirement of a target value, or
2. retain the target value and permit a symmetrical tolerances limit based on a 5% rejection rate

6.2 Data Distribution

Most statistical techniques are based on the assumption of an underlying Gaussian or normal population. Where this is grossly violated, then many of the standard statistical tests no longer apply. The distributions of data collected in this project are typically symmetrical, but are more peaked and less dispersed than the standard Gaussian distribution.

This would cause a problem if the DOT were to implement a Percent-Within-Limits (PWL) specification based on normal or Gaussian statistics. Table 20 indicates discrepancies of as much as 10% between actual counts of PWL and those computed from standard statistics – this differences being unfair to the contractor.

It is recommended that should the DOT proceed to implement a PWL specification, it should not rely on standard Gaussian statistics, but either develop specific distribution tables (e.g., Logistic as shown in chapter 5) or rely on true counts of PWL.

6.3 Regional Differences

The data collected from the six DOT districts do indeed show regional differences with regard to mean magnitudes for many of the factors. These can largely be attributed to regional geology. Of more interest, are variations in variability. The data indicate that there may be differences in variability throughout the state. There is, however, no pattern evident between the different factors and project districts.

In setting specification standards and tolerances, the DOT should be careful not to set requirements that cannot be reasonably achieved statewide. Since tolerances should be set to permit a 5% rejection level, and are under the control of the DOT, adjusted state-wide standard deviations are given in Table 23. These altered standard deviations have been desired such that no individual district would have a rejection rate of greater than 5%.

6.4 Recommendations

- It is recommended that the DOT re-examine the tolerances with respect to the voids in the compacted loose plant mix (Pa) and either (a) remove the target requirement while retaining the upper and lower limits, or (b) establish a symmetrical tolerances band around the target value with a 5% rejection level.

- Consider using the adjusted standard deviations in Table 23 to establish (or re-establish) tolerance limits to ensure that no district is unfairly disadvantaged by a 5% rejection rate.
- While not specifically addressed in this report, it is apparent that pay factors are based on the daily Quality Indices. Thus, each day's production is evaluated for payment based on the evaluation of seven (DPR) samples. This puts the contractors at greater risk, and he is more likely to "micro-manage" production by effecting many small changes to his process. Ultimately this leads to a greater variability in the finished product. It would be better to evaluate each day's production on a separate basis (e.g., mean within limits and not more than one out of seven results more than X% out of tolerance), and to make final payment decision on the completed mixture. This would more likely result in the contractor achieving an acceptable process and keeping it stable at that condition, thereby reducing overall variability.

APPENDIX. PROJECT DATA

Letting Year	Project	
1996	NHS-169-7(35)--19-46	
1997	NHSN-218-2(41)--2R-44	NHSN-218-2(42)--2R-44
	NHSN-34-2(33)--2R-69	NHSN-34-3(30)--2R-02
	STPN-15-3(8)--2J-55	STPN-63-5(41)--2J-86
	STP-69-7(20)--2C-99	STPN-1-6(22)--2J-52
	NHS-218-8(40)--19-09	NHS-218-8(48)--19-09
	STPN-169-4(52)--2J-25	
1998	NHSN-20-2(50)-2R-81	NHSN-30-2(103)--2R-24
	NHSN-30-2(79)--2R-14	STPN-110-1(9)--2J-81
	STPN-196-1(8)--2J-81	STPN-22-1(8)--2J-54
	STPN-3-7(26)--2J-33	IMN-680-2(143)12--OE-78
	STPN-169-2(19)--2J-88	NHSN-61-8(87)--2R-31
	NHSN-75-1(72)--2R-97	STPN-52-2(68)--2J-31
	STPN-6-1(87)--2J-78	STPN-276-0(1)--2J-30
	STPN-327-0(7)--2J-30	STPN-86-1(2)--2J-30
	NHSN-75-2(53)--2R-75	IM-35-6(78)163--13-35
	STPN-982-0(19)--2J-97	STPN-127-1(13)--2J-43
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	STPN-17-1(13)--2J-77	STPN-17-1(15)--2J-77
	STPN-2-3(22)--2J-87	NHS-218-9(68)--19-34
	NHS-218-9(88)--19-34	STP-10-4(9)--2C-11
	STPN-183-0(22)--2J-78	IM-29-1(45)25--13-65
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